Assessment of the impacts of building materials on the reduction of CO_2 emissions from high-rise commercial buildings in Hong Kong

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Abstract. Based on data collected in 20 A-level high-rise commercial concrete buildings in Hong Kong, the research successfully established a probability density function model, which is used to describe the carbon emissions profile of a commercial building. Results indicate that the superstructure of a commercial building, on average, had a footprint of 226.65 kg CO_2/m^2 and 10.6 kg CO_2/m^2 separately in the material use stage and transportation stages. It also evaluates the carbon emissions of various building elements and divides them into three levels according to the magnitude of their contribution. The results show that upper floor construction and external wall in Tier 1 contribute nearly 80% of emissions and should be of great concern. In addition to the probability density function model, a regression model was also successfully established in the study to predict carbon emissions. Research has shown that building layers and gross floor area can predict carbon emissions per unit area, and there is a positive relationship between the independent variable and the dependent variable. The regression model can help building designers determine design options to reduce carbon emissions in the early stages of design.

1 Introduction

Buildings account for a large proportion of total energy consumption, e.g 20% -25% of China (China Energy Statistical Yearbook, 2011) and 30% - 40% for development countries accounting (Building Energy Data Book, 2010). As for developed countries such as the United States, buildings account for about 40% of their energy use (BEDB, 2010), and the UK's construction industry accounts for 50% of its total carbon dioxide emissions (Dowden, 2008). Especially in high-density cities like Hong Kong, the construction industry consumes more than 80% of electricity and fuel energy (EMSD, 2010). Many effective measures have been implemented to reduce the energy consumption of building operations, such as solar photovoltaic systems [1], green roof [2], innovative lighting system [3], a combined cooling, heating and power system [4]. Even some studies have focused more on the possibility of zero carbon emissions.

Great success has achieved in reducing the operating energy consumption of buildings, making the carbon emissions related to building materials more and more important in the entire life cycle. Related research has proved some effective measures. The unfired clay material has shown energy-efficiency and suggests a formidable economical alternative to the firing of clay building components [5]. In reinforced concrete frame structure buildings, if prefabricated components are used instead of cast-in-place, it can be reduced by 15% Carbon dioxide emissions throughout the whole materialization stage [6]. In the end-of-life (EoL) phase of buildings, maximum reuse could save up to 38.5% of the total embodied energy of original buildings [7].

Most studies use average carbon emissions to evaluate energy consumption during the material use phase [8]. In addition, related research has developed a probability distribution graph to depict the carbon footprint caused by the materials used in the upper structure of high-rise office buildings [9]. However, few studies have combined these two carbon emission estimation methods to assess the impact of regional material selection and industrial structure adjustment. Therefore, this article proposes two research goals. First, trade scenario is proposed, and a probability distribution map is developed for scenario to depict the carbon footprint caused by the materials used in the superstructure of high-rise commercial buildings in Hong Kong. Second, its purpose is to establish a prediction model between the average carbon emissions and the physical parameters of the building.

2 System definitions and boundaries

Since there is no consensus on the boundaries of carbon dioxide emissions, it is necessary to clearly define them at

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the beginning of research. The focus of this research is to study the impact of material use options on reducing CO_2 emissions, including the initial building structure, envelope structure and internal components. The scope covers the production of building materials, the transportation from the place of production to the Hong Kong port, the construction of on-site building components, and the emissions related to material replacement. However, other impacts related to the operation of the building and the final disposal stage will be ignored. Figure 1 defines the system boundaries of this study.

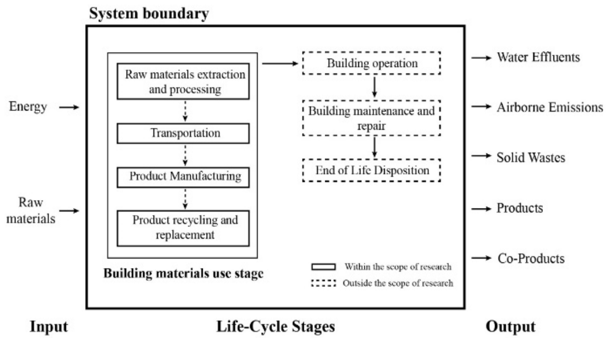

Fig. 1. Boundaries that define the processes for which their CO_2 emissions impacts have been examined for this study.

3 Methodology

20 A-level commercial buildings built between 1990 and 2005 have been selected to study their carbon dioxide emissions. The total number of floors in these buildings varies from 9 to 62.

3.1. Basic information related to building elements

Information such as gross floor area (*GFA*), storey height, building layers and the amounts of various materials are extracted from the quantity list of the construction project's bidding documents. Due to the huge amount of information about buildings, the study reintegrated the information from the unit, component classification, and various engineering indicators. For the material information of various counting units, it is necessary to convert the quantity of various building materials into their respective qualities to facilitate later calculations. In addition, according to the classification system proposed by the British Building Research Institute (BRE), the extracted information related to building materials is also grouped into appropriate building elements. Due to the inability to obtain information about the basement of all buildings, its influence was excluded in the study. The study also sorted out the various engineering indicators of each building, including the gross floor area (*GFA*), typical floor area, storey height and building layers.

The service life of building components should also be considered because the total weight of building components used in their life cycle will be affected by it. According to the concept of substitution factor of building components proposed by Chau et al. (2007) [10] for the definition of building materials, assuming that the service life of a building is 60 years, the following formula can be used to calculate the substitution factor of various building elements. To this end, we extracted the life expectancy data of different building elements from the report issued by BCIS (BCIS, 2006).

$$\textit{Replacement factor}=60/(\textit{expected lifespan (years)}) \quad (1)$$

3.2. Calculation formulation

The amount of CO_2 emitted from individual building materials was estimated by multiplying the mass of materials with the corresponding embodied energies and CO_2 emissions factors. The amount of CO_2 emitted by the ith building element ($Q_{\text{Element,I}}$, in kg CO_2) is estimated by summing up the amount of CO_2 emitted from all its constituent materials, i.e.

$$Q_{\text{Element,i}} = \sum\nolimits_1^{i} e_i \beta_i m_i \quad (2)$$

$$q_i = e_i \beta_i \quad (3)$$

where qi is the CO_2 emissions per kg of ith type building material (in kg CO_2/kg); e_i is the embodied energy intensity of the ith type of building material (in MJ/kg);

β_i is the CO_2 emission factor for the ith type of building material (in kg CO_2/MJ); and mi is the mass of the ith type of building material (in kg).

Based on the research of Chau et al. (2012) [9], we have summarized the embodied energy range for various building materials (see Table 1). In addition, scenario assumes that all construction materials in Hong Kong come from mainland China. The emission factors are calculated according to mainland China，i.e 0.01919 kg CO_2 / MJ.

Table 1. Embodied energy intensities for different types of building materials.

Type of building material	Embodied energy intensities [a] (in MJ/kg)	Average Embodied energy intensities [a] (in MJ/kg)
Aluminum	166.0–312.7	239.35
Bitumen and asphalt	3.4–50.2	26.8
Bricks and blocks	0.5–3.3	1.9
Concrete	0.7–1.6	1.15
Galvanized steel	30.6–34.8	32.7
Glass	6.8–25.8	16.3
Stone, gravel and aggregate	0.1–0.8	0.45
Purified fly ash (PFA)	<0.1	<0.1
Paint	60.2–144	102.1

Plaster, render and screed	0.1–2.0	1.05
Plastic, rubber and polymer	70.0–116.0	93
Plywood	3.1–18.9	11
Precast concrete element	2	2
Reinforcing bar and structural steel	6.2–42.0	24.1
Stainless steel	8.2–13.3	10.75
Thermal and acoustic insulation	1.2–17.6	9.4
Ceramic and tile	2.2–5.5	3.85
[a]Embodied energy values are extracted from study [9]		

The construction of buildings usually requires the transportation of large amounts of materials from countries in different geographic regions to construction sites. Although the energy and emissions associated with transportation are considered small compared with other processes, it will become more and more important as the energy consumption of other processes decreases. However, it would be very cumbersome and complicated to provide specific data and calculation tools for each building material and each country of origin. In order to simplify the data in the database and avoid misleading results, only representative values for each type of impact are calculated for each type of material, including the impact of transportation energy use, which is a weighted average of the impact of materials imported from major countries (Collectively referred to as 80% or more of the total imports of this material). Based on Hong Kong trade statistics, the weight used in this calculation is a percentage of the quantity imported by each country. The transport energy of each material is calculated in this way, based on the following Transport Energy Agency utilization rates, as shown in Table 2 below:

Table 2. Transportation energy use rates

Transportation energy use	(MJ/Kg-km)
Land, distance < 50km	0.0027
Land, distance > 50km	0.001
Deep sea transport	0.0002

The method used is similar to that of Chen et al. (2001) [11]. The calculation takes into account two modes of transportation, the first is the distance of the material from the factory to the sea port of the country of origin, the second is the distance from the sea port of that country to Hong Kong.

3.3. PDF model and regression model

The purpose of the study is to estimate the range and average value of carbon emissions at the same time, so as to be able to explore more different energy-saving measures. Specifically, a probability density function model was established to explore the range of CO_2 emissions produced by various materials in commercial buildings; and a multiple linear regression model was used to explore the relationship between various engineering indicators and carbon emissions (average value) at the initial design stage. Combining the two methods can provide a more comprehensive understanding of the carbon emissions of commercial buildings from different dimensions.

The Monte Carlo method is used to generate the probability distribution of CO_2 emissions from various materials [9]. We used a computer software called Python for model development. The whole process is as follows. First, a model distribution that is completely similar to the actual situation is developed, and then the distribution of input variables containing uncertainty is defined through Python. The correctness or correctness of these distributions is checked by goodness of fit (GOF) statistics. Once the basic distribution is determined, Python is applied to generate random values. Random values are used to estimate the probability density function (PDF) of emissions. PDF can take several different forms (such as Gamma, Lognormal, Weibull and Normal). Finally, use carbon emission formulas Eq. (1), Eq. (2) and Eq. (3) to summarize the PDF.

Another purpose of the research is to build a multiple regression model to predict carbon emissions per unit area. The calculation formula is as follows:

$$Y_i = \alpha + \sum\nolimits^{k}_{i=1} \beta_k X_{ki} + \varepsilon_i \qquad (4)$$

where Y_i represents the dependent variable of carbon emission per unit, and β_k the estimated coefficients which maximize the function given the value of the independent variable X_{ki}. Each coefficient provides a partial explanation of the dependent variable associated with the sample data.

4 Results and analysis

Two models were successfully constructed in the research. The probability density function (PDF) model is constructed using the Monte Carlo method based on the p value less than 0.05, while the multiple regression model can effectively predict the relationship between carbon emissions per unit area and various construction engineering indicators.

4.1. Formation and analysis of PDF model

Table 3 and Table 4 list the basic parameter values that characterize the probability density function (PDF). The function in Table 3 depicts the weight distribution of different building elements and materials, and Table 4 depicts the CO_2 emissions factor of different building materials in trade scenario.

Table 3. PDFs portraying mass distributions of different building elements and types of materials.

Building element	Major material group	Type of PDF [a]	Mass per construction floor area (in kg/m^2)
Doors	Plastic	Weibull	0.02-0.51
	Plywood	Lognormal	0.02-0.94
	Stainless steel	Gamma	0.04-0.73
External walls	Aluminum	Weibull	1.8-10.47
	Concrete	Lognormal	44.82-603.91
	Reinforcing bar	Lognormal	3.31-70.8
	Stainless steel	Lognormal	0.15-1.71
	Stone	Lognormal	0.20-2.20
Floor surfacing and finishes	Galvanized steel	Weibull	0.02-4.77
	Plaster	Weibull	0.05-0.51
	Stone	Gamma	0.66-13.21
	Tile	Lognormal	0.30-9.39
Internal walls and partitioning	Bricks and blocks	Lognormal	8.08-227.39
	Concrete	Gamma	16.32-141.79
	Galvanized steel	Weibull	0.04-8.48
	Glass	Gamma	0.01-3.06
	Reinforcing bar	Weibull	1.30-10.01
	Stainless steel	Weibull	0.01-0.84
Paint system	Paint	Lognormal	0.07-0.85
Roof construction	Concrete	Lognormal	0.28-5.86
	Galvanized steel	Gamma	0.30-9.73
	Plaster	Cauchy	4.10-16.63
	Stone	Lognormal	0.31-2.59
	Tile	Cauchy	0.69-2.32
Roof insulation	Asphalt and bitumen	Gamma	0.10-3.18
	Plaster	Weibull	0.33-13.32
	Thermal insulation	Normal	0.03-0.34
Suspended ceilings and ceilings finishes	Acoustic insulation	Lognormal	0.10-5.72
	Aluminum	Lognormal	0.14-1.67
	Galvanized steel	Weibull	0.01-7.54
	Plaster	Lognormal	0.58-8.58
	Thermal insulation	Weibull	0.10-8.72
Upper floor construction	Concrete	Cauchy	480.93-1825.48
	Galvanized steel	Gamma	0.13-50.97
	Plaster	Normal	0.10-6.64
	Reinforcing bar	Lognormal	13.83-357.28
	Structural steel	Weibull	0.33-100.55
	Tile	Gamma	0.10-1.85
Wall finishes	Aluminum	Lognormal	0.01-0.91
	Galvanized steel	Gamma	0.10-1.72
	Plaster	Normal	6.64-41.85
	Stone	Lognormal	0.57-13.49
	Tile	Weibull	0.14-10.32
Wall insulation	Plaster	Weibull	0.7-7.61
	Thermal insulation	Weibull	0.18-22.10
Windows/curtain wall	Aluminum	Gamma	0.10-0.83
	Glass	Gamma	3.10-33.30

[a]Type of weight distribution as selected by the results derived from the significance of Kolmogorov–Smirnov test and Anderson–Darling test.

Table 4. PDFs portraying CO_2 emission factor distributions of different types of building materials in scenario.

Type of building material	Scenario	
	Type of PDF[a]	CO_2 emission factors (in kg CO_2/kg)
Aluminum	Uniform	3.186-6.001
Bitumen and asphalt	Uniform	0.065-0.963
Bricks and blocks	Uniform	0.010-0.063
Concrete	Uniform	0.013-0.031
Galvanized steel	Uniform	0.587-0.688
Glass	Uniform	0.130-0.495
Stone, gravel and aggregate	Uniform	0.002-0.015
Purified fly ash (PFA)	Point	0.001919
Paint	Uniform	1.155-2.763
Plaster, render and screed	Uniform	0.002-0.038
Plastic, rubber and polymer	Uniform	1.343-2.226
Plywood	Uniform	0.059-0.363
Precast concrete element	Point	0.03838
Reinforcing bar and structural steel	Uniform	0.119-0.806
Stainless steel	Uniform	0.157-0.255
Thermal and acoustic insulation	Uniform	0.023-0.338
Ceramic and tile	Uniform	0.042-0.106

[a]Type of embodied energy factor distribution is selected by the significance of Kolmogorov–Smirnov test and Anderson–Darling test.

Based on the basic parameter values of the building components, a probability density function model of trade scenario was constructed to describe the CO_2 emission characteristics of the superstructure of a commercial building (excluding transportation), as shown in Fig.2 and it can be used to classify commercial buildings into different performance levels A-D. Frequency band A represents the lowest CO_2 emissions, and frequency band D represents the highest emissions. The profile assumes a lognormal PDF with an average emission value of 226.65 kg CO_2/m^2 (95% CI: 180.98–272.33 kg CO_2/m^2). In addition, the average carbon emissions during the transportation phase are 10.6 kg CO_2/m^2 (4.5%), which is far less than the 226.65 kg CO_2/m^2 (95.5%) produced during the material use phase.

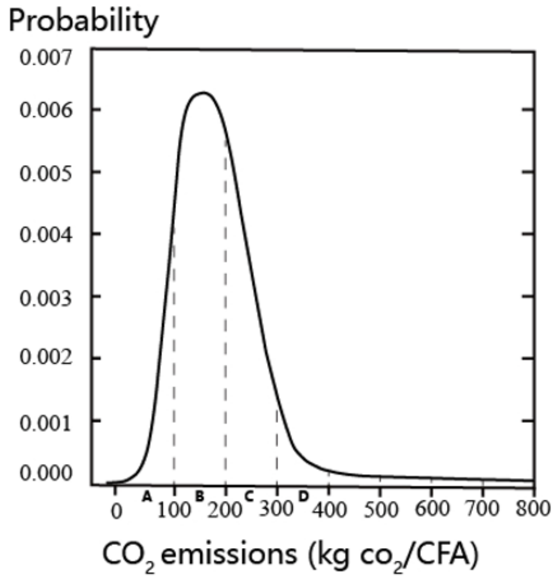

Fig. 2. The probability density function shows the overall CO_2 emission profile of the superstructure of a new commercial building in trade scenarios.

Fig. 3 shows the ranges of CO_2 emission values for different commercial building elements. According to the proportions of various building elements shown in Fig. 3, CO_2 emission of commercial building elements can be roughly divided into three levels. The first level is the two most contributing parts, including upper floor construction and external wall, which together contribute nearly 80% of CO_2 emissions. The second level is the building elements whose contribution rate are more than 2%, including suspended ceilings and ceilings finishes, internal walls and partitioning, windows/curtain walls and floor surfacing and finishes, together contribute to nearly 15% of CO_2 emissions. The third level is the other six building elements whose CO_2 contribution rate are less than 2%. Since the proportion of the first level is much larger than that of the other levels, we further study the CO_2 contribution rate of construction materials related to upper floor construction and external wall. Table 7 shows the average contribution of the materials that make up the two main building elements in three scenarios. Among these two building elements, concrete accounts for approximately 20% of total carbon emissions, while reinforcing bars account for nearly 24%. In other words, these two materials provide nearly half of the contribution in total CO_2 emissions. Attention should also be paid to the galvanized steel (3.4%) and structural steel (9.4%) of upper construction because they also play a significant role. As far as the exterior wall is concerned, aluminum contributes most of the CO_2 emissions.

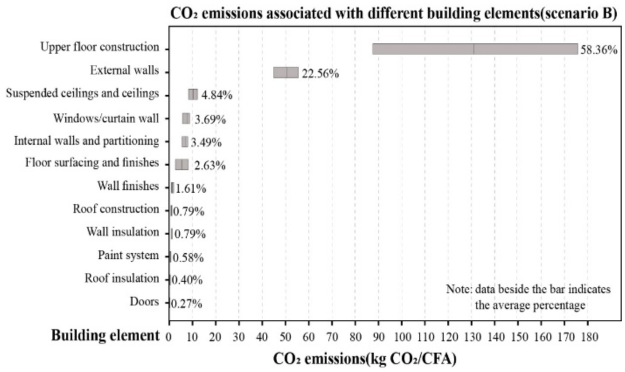

Fig. 3. Range of CO_2 emission values for different building elements in trade scenario.

Table 5. Average contribution of the materials constituting the two major building elements.

Building element	Material	Average contribution[a]
		scenario
Upper floor construction	Concrete	19.25%
	Galvanized steel	3.39%
	Plaster	0.02%
	Reinforcing bar	23.64%
	Structural steel	9.42%
	Tile	0.03%
External walls	Aluminum	12.48%
	Concrete	3.21%
	Reinforcing bar	5.81%
	Stainless steel	0.06%
	Stone	0.01%

[a]Contribution refers to the percentage of total CO_2 emissions.

4.2. Formation and analysis of multiple regression model

In the initial design of commercial buildings, parameters such as the gross floor area (*GFA*), typical floor area, storey height and building layers will be the main considerations for designers. This study will initially use the four factors mentioned above as variables, analyse their correlation with CO_2 emissions per unit area (mean value), and conduct a preliminary screening of the influencing factors of carbon emissions. Table 6 shows the abbreviations of each variable for future research.

Table 6. Variables and their corresponding units and abbreviations.

Term	Abbreviation	Unit
Gross floor area	*GFA*	m^2
Typical floor area	*S*	m^2
Storey height	*H*	m
Building layers	*N*	-
CO_2 emissions per unit area	LCO_2	kg CO_2/CFA

It can be seen from Table 7 that all variables except *H* (significance level 0.536) have good correlation with LCO_2, and all pass the significance level test (significance level is less than 0.01). In addition, because the magnitude of *GFA* is larger than other variables and there is a certain quantitative relationship between *GFA* and *S*, *N*. The correlation between *S*, *N* and LCO_2 will be analysed separately to avoid large errors.

Partial correlation analysis (also known as net correlation analysis) can analyse the linear correlation between two variables and calculate the partial correlation coefficient under the condition of controlling the linear influence of other variables, so it can more accurately reflect the correlation between variables. Therefore, this study uses partial correlation analysis to explore the correlation between LCO_2 and *S*, *N*. As shown in Table 8, *N* passes the significance level test (significance level is less than 0.05) and S fails the significance level test. In summary, LCO_2 has a correlation with *GFA* and *N*.

Table 7. Correlation analysis of five different variables and CO_2 emissions per unit area.

		GFA	*S*	*H*	*N*
LCO_2	Pearson's Correlation	0.877**	0.590**	0.151	0.761**
	Sig.(2-tailed)	0.000	0.000	0.536	0.000
	N	20	20	20	20

**. Correlation is significant at the 0.01 level (2-tailed).

Table 8. Partial correlation of CO_2 emissions per unit area and various variables.

		S	*N*
GFA	Pearson's Correlation	0.160	0.498*
	Sig.(2-tailed)	5.270	0.035
	N	20	20

*. Correlation is significant at the 0.05 level (2-tailed).

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Bivariate analysis and partial correlation analysis can describe the closeness of the relationship between variables. And regression analysis can infer the information of unknown variables based on the information of known variables by determining the corresponding mathematical expressions between variables. This study will mainly design a regression model based on the aforementioned correlation analysis results to determine the regression variables and their impact on CO_2 emissions. We choose multiple linear regression analysis to establish a building material life cycle prediction model, with LCO_2 as the dependent variable and *GFA*, *N* as the independent variables. The regression analysis results are as follows:

$$LCO_2=102.866+0.002GFA+2.294N\ (R^2=0.826) \quad (1)$$

Since R^2=0.826 is very close to 1, the regression model was successfully established. That is to say, CO_2 emissions can be effectively predicted through engineering indicators.

5 Discussions and conclusions

The research successfully established a PDF model. The PDF model is used to describe the CO_2 emission profile of a commercial building. It evaluates the carbon emissions of various building elements and divides them into three levels according to the magnitude of their contribution. The two elements (upper floor construction and external wall) in Tier 1 contribute nearly 80% of emissions and should be of great concern. This study also deeply analysed the material composition of these two elements and the carbon emission of each material. Because our models are based on data collected from 20 high-rise commercial buildings, they are more comprehensive than previous studies, and its data is more valuable. The data generated by the PDF model also helps to further discuss the options for reducing the carbon emissions generated during the material use stage.

In addition to the PDF model, a regression model was also successfully established in the study to predict carbon emissions. The regression model can help building designers determine design options to reduce carbon emissions in the early stages of design. Research has shown that building layers and *GFA* can predict CO_2 emissions per unit area, and there is a positive relationship between the independent variable and the dependent variable. That is to say, if the building layers and *GFA* of commercial buildings in Hong Kong can be restricted, it will have a positive impact on CO_2 emissions.

Although the research has considered carbon emissions from multiple dimensions and aspects, it may still suffer from many shortcomings, which may limit its practicality. First of all, during the establishment of the PDF model, due to the limitation of the data sample size, the estimation of the carbon emission range will have errors. Similarly, the size of the sample size also has an impact on the establishment of the regression model. Secondly, the carbon emissions generated by transportation need to be calculated more carefully. Third, the research ignores the impact of material waste management systems and material recycling. Finally, our findings should also be limited to the reinforced concrete buildings we sampled from.

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